

EVALUATION OF MPLM DESIGN AND MISSION 6A COUPLED LOADS ANALYSES

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ABSTRACT

Through the development of a space shuttle payload, there are usually several coupled loads analyses (CLA) performed: preliminary design, critical design, final design and verification loads analysis (VLA). A final design CLA is the last analysis conducted prior to model delivery to the shuttle program for the VLA. The finite element models used in the final design CLA and the VLA are test verified dynamic math models.

Mission 6A is the first of many flights of the Multi-Purpose Logistics Module (MPLM). The MPLM was developed by Alenia Spazio S.p.A. (an Italian aerospace company) and houses the International Standard Payload Racks (ISPR) for transportation to the space station in the shuttle. Marshall Space Flight Center (MSFC), the payload integrator of the MPLM for Mission 6A, performed the final design CLA using the M6.0ZC shuttle data for liftoff and landing conditions using the proper shuttle cargo manifest. Alenia performed the preliminary and critical design CLAs for the development of the MPLM. However, these CLAs did not use the current Mission 6A cargo manifest. An evaluation of the preliminary and critical design performed by Alenia and the final design performed by MSFC is presented.

NOMENCLATURE

$[M_g]$	generalized mass matrix
$[C_g]$	generalized damping matrix
$[K_g]$	generalized stiffness matrix
$\{q_{dd}(t)\}$	normal mode coordinates of accelerations
$\{q_d(t)\}$	normal mode coordinates of velocities
$\{q(t)\}$	normal mode coordinates of displacements
$[\Phi^*]^T$	transpose of the coupled system modes
$\{F(t)\}$	forcing functions
ζ	percentage of the critical damping

$\{L(t)\}_{i/f \text{ mplm}}$	interface forces
$[FTM1^*_{mplm}]$	force transformation matrix
$[FTM2^*_{mplm}]$	force transformation matrix
$\{L(t)\}_{ncca \text{ mplm}}$	net CG accelerations
$[A_{cc}]$	relates boundary DOF to CG
$[RBT]$	rigid body transformation
$[M_{bb}]$	Craig-Bampton mass matrix boundary partition

1 INTRODUCTION

The International Standard Payload Racks (ISPR) (Figure 1), will be used to contain all experiment, systems, and operational equipment in the space station. The Multi Purpose Logistics Module (MPLM) (Figure 2), will house the racks for transportation to the space station in the shuttle. Before any

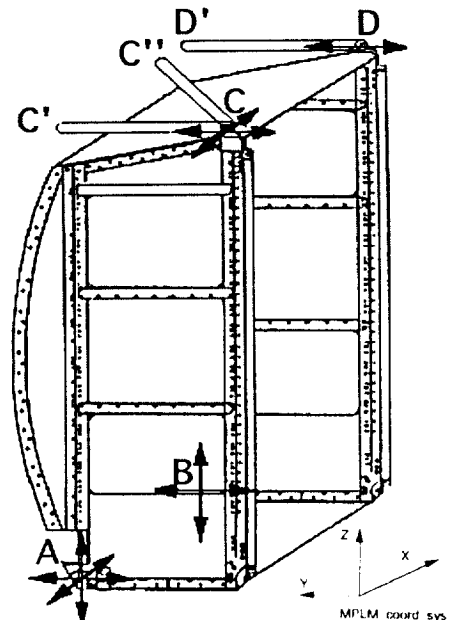


Figure 1: International Standard Payload Rack

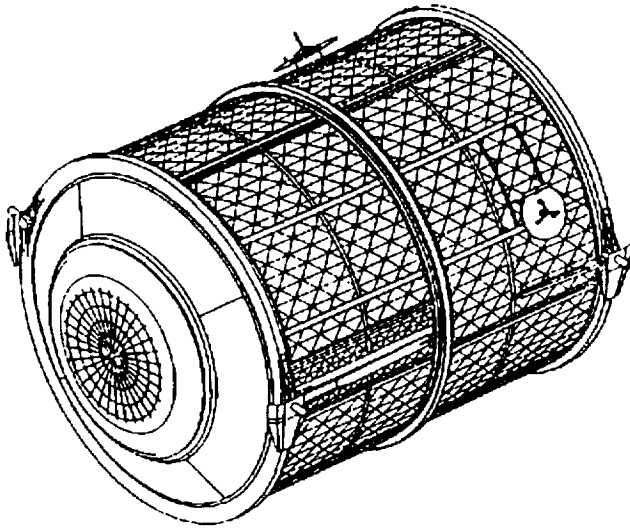


Figure 2: The Multi Purpose Logistics Module

payload can fly on the shuttle a coupled dynamic loads analysis must be performed. This is to characterize the interaction of the payload dynamics with the shuttle structure and its associated forcing functions. The coupled loads analysis is used to quantify shuttle/cargo interface forces, cargo/rack interface forces, and various internal rack loads.

The critical design review coupled loads analysis is usually the last time an analysis is performed before the VLA which is the last analysis before launch. The MPLM will be flown many times during the life of the space station. The MPLM can be configured in different ways, number of racks, weight of racks, location of racks in the MPLM, and location of the MPLM in shuttle. Other payloads can also fly in the shuttle's bay. Since there are many different configurations each time the MPLM flies, a mission specific coupled loads analysis may be required.

Once a manifest for a mission is decided upon, a final design coupled loads analysis may be conducted. The results from this analysis are compared to the MPLM allowables to verify that the racks do not over load the MPLM and the interface fittings. From the MPLM CDR CLA^[2] and previous MPLM CLAs the MPLM load allowables^[3] were defined. For Mission 6A^[1] the manifest consists of thirteen racks, (Figure 3). There are six system racks (the Avionics #3 (AV3) rack, the DC/DC Converter Unit racks #1 and 2 (DDCU1 and DDCU2), the Mobile Servicing System (MSS) rack, and the Crew Health Care Systems (CHCS) rack) modeled by Boeing North American (BNA)/Huntsville, four Resupply Stowage Racks (RSR) and two Resupply Stowage Platform (RSP) both models provided by BNA/Houston, and the Human Research Facility (HRF) modeled by Lockheed-Martin. The test verified empty MPLM dynamic model was supplied by Alenia. The

Spacelab Logistics Platform (SLP) dynamic model was developed by MSFC. BNA/Downey supplied the shuttle models for liftoff and landing configurations and include the "Verification Cycle" version Super Light Weight Tank (SLWT) model and the one-tie, lightweight steel case joint redesign solid rocket boosters with the modified aft skirt stiffness along with the LR5000V series liftoff forcing functions.

2 METHODOLOGY

For Mission 6A the coupled system model is a synthesis of the MPLM/rack integrated cargo element, SLP cargo element, and the shuttle dynamic models. These models are in Craig-Bampton^[4] reduced form. The mass and stiffness matrices for the coupled system were formed by overlaying the mass matrices and the stiffness matrices at the cargo elements/shuttle interface DOF. The mode shapes and natural frequencies used in the transient response analysis are obtained from the eigenvalue solution of the coupled system models. Modes through 35 Hz were retained for liftoff, abort landing, and normal landing coupled system configurations.

The general equation of motion for the coupled system model is:

$$[M_g]\{q_{dd}(t)\} + [C_g]\{q_d(t)\} + [K_g]\{q(t)\} = [\Phi^*]^T\{F(t)\} \quad (1)$$

where $[M_g]$, $[C_g]$, and $[K_g]$ are the generalized mass (unity), damping (diagonal $[2\zeta\omega]$), and stiffness (diagonal $[\omega^2]$) matrices, respectively. $[\Phi^*]^T$ is the transpose of the coupled system mode shapes, $\{F(t)\}$ is the time history of externally applied forces acting on the space transportation system vehicle, or forcing functions, and $q_{dd}(t)$, $q_d(t)$, $q(t)$ are the normal mode coordinates of accelerations, velocities, and displacements, respectively.

Equation 1 is solved using an exact solution for $q_{dd}(t)$, $q_d(t)$, and $q(t)$ at time intervals of 0.005 seconds. Internal results are recovered using transformation matrices with the generalized accelerations and externally applied forces. The modal damping term, ζ , is based on the forcing functions supplied by BNA/Downey. A variability factor is applied to the elastic body modes to account for uncertainties in math model and forcing function changes and cargo manifest changes that may occur prior to the verification loads analysis cycle.

Load Transformation Matrices (LTM's) were used to recover the payload loads in terms of physical coordinates from the generalized accelerations and externally applied forces. The recovery of MPLM/orbiter and MPLM/rack interface forces is described in the expression:

$$\{L(t)\}_{i/f \text{ mplm}} = [FTM1^*_{mplm}]\{q_{dd}(t)\} + [FTM2^*_{mplm}]\{F(t)\} \quad (2)$$

where $[FTM1^*_{mplm}]$ and $[FTM2^*_{mplm}]$ are the force transformation matrices describing physical DOF in terms of coupled

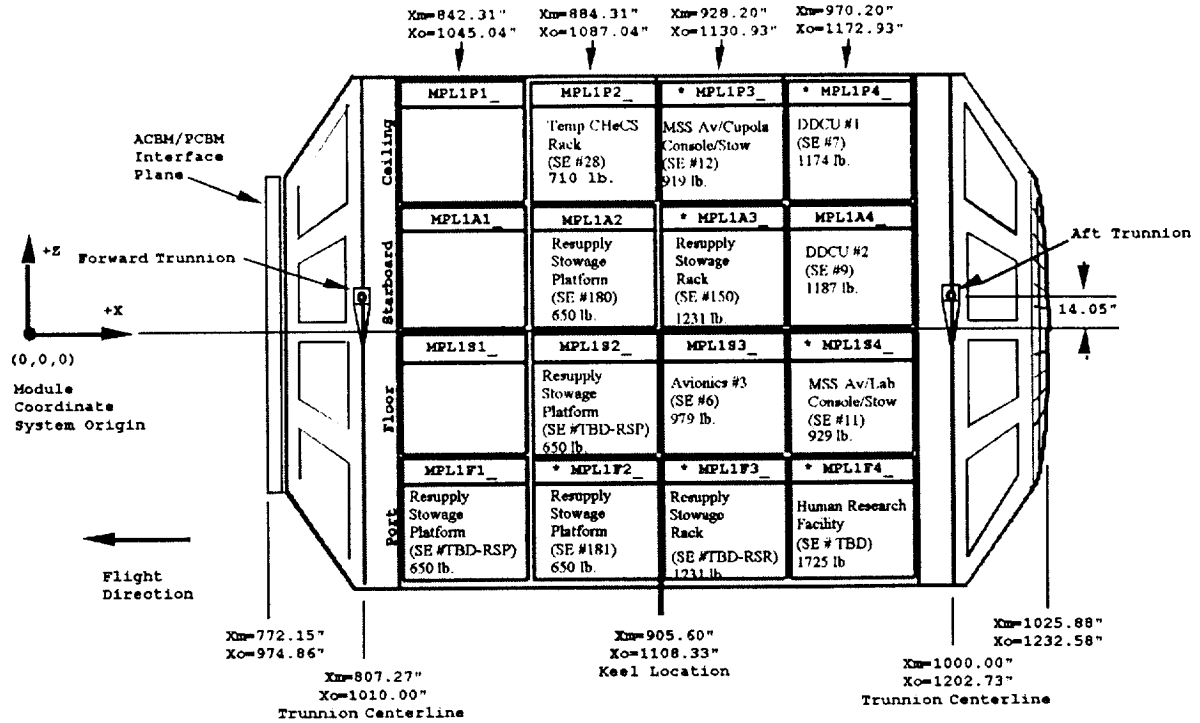


Figure 3: Rack Liftoff Configurations in the MPLM

system modal accelerations and externally applied forces, respectively. $\{q_{dd}(t)\}$ is the generalized (modal) accelerations, and $\{F(t)\}$ is the applied force time histories, both from the solution of the transient response (Equation 1).

Integrated MPLM/racks CG net accelerations were recovered by premultiplying the force transformation matrices by the transformation matrix, $[A_{cc}]$, which relates the boundaries of the MPLM/rack to the MPLM/rack subsystem CG and the boundaries of the rack to the rack CG:

$$\{L(t)\}_{n_{cga} \text{ mptm}} = [ACG^*_{mptm}]\{q_{dd}(t)\} \quad (3)$$

where $[ACG^*_{mptm}] = [A_{cc}][FTM1^*_{i/f}]$
 $[A_{cc}] = \frac{1}{386.09} ([RBT]^T [M_{bb}] [RBT])^{-1} [RBT]^T$.

$[RBT]$ is the rigid body transformation from the boundary DOF to the CG, $[M_{bb}]$ is the Craig-Bampton mass matrix boundary partition, and $\{q_{dd}(t)\}$ is the generalized (modal) accelerations from the solution of the transient response (Equation 1).

3 RESULTS

A case-by-case direct comparison between Alenia's CDR CLA and the Mission 6A specific final design CLA can not be made due to several differences in the configuration of the

racks in the MPLM and the analysis data used. The model of the MPLM used in both analyses is the same test verified model. The CDR CLA used three MPLM configurations, Heavy (13879 Kg), Light (8742 Kg), and Extra Light (7288 Kg) where the FDLAC liftoff and Abort Landing was 10483 Kg, and the Nominal Landing of 7171 Kg. The racks that the CDR CLA used were generic ISPR's which had evenly distributed mass on four shelves. Four different configurations (804.7 Kg, 544.8 Kg, 454.1 Kg, and 363.5 Kg) of the ISPR's were used. The FDLAC used specific rack configurations for the mission, (Figure 3).

Since the FDCLA was run after the CDR CLA, new shuttle models were available. The FDCLA used the M6.0ZC Shuttle model. The Shuttle liftoff model is comprised of the "Verification Cycle" version super light weight tank (SLWT) model, the one-tie lightweight steel case joint redesign solid rocket booster (SRB) model with modified aft skirt stiffness, the Remote Manipulator System (RMS) arm model, the Orbiter model, the Orbiter Docking System (ODS) model, the Remotely Operated Fluid Umbilical (ROFU) model, the Remotely Operated Electrical Umbilical (ROEU) model, and bridge fitting models. The CDR CLA used the M6.0ZB04 Shuttle model which varied in the SLWT model, thus a different set of liftoff forcing functions was used in the analysis (LR5000 for MPLM CDR CLA and LR5000V for FDCLA).

Due to the different configurations of the MPLM, the integrated

TABLE 1: Liftoff - Rack Interface Forces

Grid & Direction	MPLM CDR CLA (N)	FDLAC (N)	ICD (N)
By	12970	14368	29500
Bz	32110	21218	38100
Ax	28740	19483	30500
Ay	13600	11432	27800
Az	27920	31138	37100
C'y	15400	13256	
C"x	21050	14346	
C'y	13560	9697	
D'y	11800	11699	

Shuttle system's Center of Gravity (CG) is different. The landing forcing functions are generated by the location of the Shuttle's CG and location of the items in the Shuttle's cargo bay (MPLM in same location for both analyses). The Shuttle's system's CG of the Light configuration of the CDR CLA was close enough to the FDCLA that the same landing forcing functions were utilized (LE7510, LG7511 thr LG7516).

The SLP was also included in the Shuttle's cargo bay for the analyses. The MPLM CDR CLA used two different generic SLP models of 3302.4 Kg and 1248.1 Kg for the Light and Extra-Light configurations, respectively. A mission specific configured SLP (Space Station Remote Manipulator System, etc) was included in the FDCLA for Mission 6A which had a mass of 3382.3 Kg for liftoff and 1200.8 Kg for landing.

The same damping values were the same for both analyses. Damping is used in the form of a percentage of the critical damping:

Liftoff ζ = 1.0 percent for modes < 10 Hz
 ζ = 2.0 percent for modes > 10 Hz
 Landing ζ = 1.0 percent for all modes.

Since Alenia's CLA was at the CDR level a variability factor of 1.25 was applied to the all the dynamic responses. The FDCLA is the last load cycle before the verification load analysis. Since the models used for the FDCLA were at different levels of maturity (test verified or not) different variability factors were applied. The MPLM had variability factors of 1.0, 1.1 was used for the racks, and 1.25 for the SLP.

Due to the differences of the configurations the maximum values for each analysis were considered for comparison. In addition to the two CLA's, the Design Limit Loads and the Rack Acceleration from the "Rack to Mini Pressurized Logistics Module Interface Control Document (Rack-to-MPLM ICD)^{3*}" are present for comparison, Table 2.

TABLE 2: Landing - Rack Interface Forces

Grid & Direction	MPLM CDR CLA (N)	FDLAC (N)	ICD (N)
By	11430	11432	26470
Bz	22940	15658	57206
Ax	27750	15480	33863
Ay	14000	10409	24571
Az	32740	20239	57108
C'y	15460	11254	
C"x	18100	12055	
C'y	11600	7740	
D'y	13440	7384	

TABLE 3: Liftoff - Rack Center of Gravity Accelerations

Direction	MPLM CDR CLA	FDLAC	ICD
X (g)	6.86	7.0/-5.6	7.00
Y (g)	5.77	4.9	8.00
Z (g)	6.57	9.1	7.80
RX ($\frac{rad}{s^2}$)	42.42	44.5	70.80
RY ($\frac{rad}{s^2}$)	12.40	14.8	21.70
RZ ($\frac{rad}{s^2}$)	19.37	19.2	34.80

The data in the Rack-to-MPLM ICD are the design loads and the mission specific results can not exceed these values. The ICD reports rack interface forces at upper rack attach points C and D of the rack which does not include the knee braces (Figure 1). The FDCLA and the MPLM CDR CLA recovered the loads at the points where the rack interfaces with the MPLM (C', C'', D').

The MPLM's interface with the Shuttle is the most critical to astronaut safety. These interfaces consists of seven degrees of freedom (DOF), two primary trunnions with DOF in the X and Z direction, two secondary trunnions with DOF in the Z direction and a Keel with DOF in the Y direction.

TABLE 4: Landing - Rack Center of Gravity Accelerations

Direction	MPLM CDR CLA	FDLAC	ICD
X (g)	6.36	5.1	5.30
Y (g)	6.49	5	7.20
Z (g)	6.91	6.0/-2.8	9.00
RX ($\frac{rad}{s^2}$)	22.97	17.4	37.10
RY ($\frac{rad}{s^2}$)	12.56	10.7	23.00
RZ ($\frac{rad}{s^2}$)	17.62	22.32	28.30

TABLE 5: Liftoff - MPLM to Shuttle Trunnion Interface Forces

Trunnion	Dir	CDR CLA (N)	FDLAC (N)
Sec -Y	Z	118700	74863
Sec +Y	Z	118900	64321
Pri -Y	X	241000	172813
Pri -Y	Z	94820	80468
Pri +Y	X	228300	159957
Pri +Y	Z	89220	82292
Keel	Y	85710	53200

TABLE 6: Landing - MPLM to Shuttle Trunnion Interface Forces

Trunnion	Dir	CDR CLA (N)	FDLAC (N)
Sec -Y	Z	172400	93679
Sec +Y	Z	167600	88697
Pri -Y	X	161100	131845
Pri -Y	Z	213600	113296
Pri +Y	X	176800	140341
Pri +Y	Z	232800	108314
Keel	Y	92290	71216

4 CONCLUSION

Since the MPLM CDR CLA and the Mission 6A FDCLA configurations are different, only the overall maximum interface forces and rack CG load factors can be compared. All the liftoff interface forces from the FDCLA were less than the MPLM CDR CLA and the ICD, except for the By and Az rack interfaces. The FDCLA By and Az interfaces were 1398 N (11%) and 3218 N (12%) higher than the CDR CLA, but significantly lower (51% and 16%, respectively) than the ICD. The landing FDCLA interface forces were all lower than the MPLM CDR CLA.

There were several FDCLA rack CG accelerations that exceeded the MPLM CDR CLA. The liftoff FDCLA was higher by $0.14g$, $2.53g$, $2.08 \frac{rad}{s^2}$, and $2.4 \frac{rad}{s^2}$, for X, Z, RX, RY (2%, 39%, 5%, and 19%) respectively and landing $4.7 \frac{rad}{s^2}$ (27%) for RZ. The liftoff Z direction CG acceleration exceeded the ICD value by $1.3g$ (17%). The RSP was the rack where the high loads occurred. The RSP model used for the FDCLA was discovered to be designed stiffer than the MPLM with respect to the attach points, which could have caused the higher loads. All the exceeded values were the result of the RSP except for the liftoff X and RY which were due to the AV3 rack. The shuttle to MPLM interface forces from the FDCLA are enveloped by the MPLM CDR CLA.

It was expected that some of the FDCLA values would exceed the MPLM CDR CLA due to the differences in the coupled loads analyses. However, the Z direction CG acceleration of the RSP exceeding the ICD was unexpected. A redesign of the RSP is in progress. It was observed that the MPLM is sensitive to the configuration of the racks in the MPLM and the mass of those racks.

REFERENCES

- [1] **Ricks, Ed and Bookout, Paul S.**, *Multi Purpose Logistics Module (MPLM) Delta Final Design Cycle Coupled Loads Analysis for Mission 6A Using M6.0ZC Shuttle Data for Liftoff and Landing Conditions*, NASA - Marshall Space Flight Center, ED23(98-102), 1998.
- [2] **Bellini, Marina and Fleming, Paolo**, *MPLM/STS Coupled Load Analysis and Results*, Alenia, Aerospazio Space Division, MLM-RP-AI-0254, 1998.
- [3] **International Space Station Program (ISSP)**, *Rack to Mini Pressurized Logistics Module Interface Control Document (ICD), Part 1 and 2*, NASA - ISSP - Johnson Space Center, SSP 410017, Rev. C, 1998.
- [4] **Craig, Roy R. and Bamptom, M.C.C.**, *Coupling of Substructure for Dynamic Analysis*, AIAA J., pp.1313-1319, 1968.